Meteor head echoes - observations and models

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Abstract. Meteor head echoes – instantaneous echoes moving with the velocities of the meteors – have been recorded since 1947. Despite many attempts, this phenomenon did not receive a comprehensive theory for over 4 decades. The High Power and Large Aperture (HPLA) features, combined with present signal processing and data storage capabilities of incoherent scatter radars, may give an explanation for the old riddle. The meteoroid passage through the radar beam can be followed with simultaneous spatial-time resolution of about 100 m-ms class. The current views of the meteor head echo process will be presented and discussed. These will be related to various EISCAT observations, such as dual-frequency target sizes, altitude distributions and vector velocities.

Key words. Interplanetary physics (Interplanetary dust) – Radio science (General and miscellaneous) – General and miscellaneous (New fields)

1 Introduction

The very first meteor head echo observations by radar were reported by Hey et al. (1947). The authors speak about "faint fast-moving echoes from the ionisation in the immediate vicinity of the approaching meteors, in addition to the stronger and more enduring broadside reflections from the meteor trains or streaks". The concept of "head echo" is probably first mentioned in Millman and McKinley (1949) as an instantaneous head echo moving with the velocity of a meteor. Only the feature is presented in this paper: a full discussion of the various echo forms that may be produced and the reasons for their appearance was not possible at that time. A longer theoretical paper (McKinley and Millman, 1949) presented the head echo characteristics: no measurable endurance and range-time motion, apparently corresponding to the geocentric velocity of the meteoroid. They also give the first explanation for the head echoes: the instantaneous ionisation caused by intense ultra-violet light at some distance from the meteor head.

During the following 40 years a half dozen models have been introduced to explain all the observational features connected to head echoes. These will be briefly presented in the next section. Jones and Webster (1991) presented a thorough analysis on visual and radar studies of meteor head echoes. They say that "even after 4 decades there is still no comprehensive theory which explains all the features associated with head echoes" and conclude that a prerequisite for a head echo scattering theory is a detailed knowledge of the ionised coma in the vicinity of a single meteoric grain. Even Steel and Elford (1991) conclude in their paper about radio meteor height distributions that further experimental work aimed at determining the true height distribution may need to use completely different techniques from the ones used in meteor radars.

The first meteor observations with EISCAT Incoherent Scatter Radars were run in December 1990 at about the same time as the conclusions above concerning the need for new experimental methods were drawn (Pellinen-Wannberg and Wannberg, 1994). This occurred by accident without any knowledge of meteor science at that time. The purpose was to study meteor shower influence on sporadic E-layers and their ion content. Observing meteors with incoherent scatter radars was not a completely new effort; studies had been done in the 1960s at the Royal Radar Establishment in Malvern (Greenhow and Watkins, 1964) and with the Millstone Hill radar at Haystack (Evans, 1965, 1966). At Arecibo meteor echoes had been a problem in connection with the regular E-region incoherent scatter measurements and great efforts have been made to remove them (German and Mathews, 1986; Zhou and Mathews, 1994).

A comparison between the meteor and High Power and Large Aperture (HPLA) radars, based on the beam width and power, results in 3–4 order of magnitude larger power densities at the 100-km range for the latter. Thus, the HPLA features that the incoherent scatter radars can offer, even though at higher frequencies, seem to be what is needed to be able to penetrate the ionisation cloud to the close vicinity of the fast moving meteoroid.

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2 Classical head echo models

The head echo models that were suggested during the 1940s to 1960s differed greatly. There seem to have been considerable controversy, discussion and criticism of competing theories. (See the original papers referenced in this paper and the references therein.) Here we present only the main features of those models.

McKinley and Millman discuss meteor head echoes in several papers. "A phenomenological theory of radar echoes from meteors" (McKinley and Millman, 1949) discusses the production of ionisation by two mechanisms. The first is kinetic transfer through collisions involving both meteoric and air particles, the action occurring in the immediate vicinity of the meteoroid. The second is a radiation energy transfer produced by ultraviolet light from the meteor, which may be immediately effective at a considerable distance from the meteoroid. This second mechanism was added since it was believed that the diffusion of the ionisation produced by collision was too slow to produce immediately a cloud big enough to reflect the 9-m radio waves. A further problem has been the required fast disappearance of the ionisation.

Browne and Kaiser (1953) suggest a model in terms of the familiar diffraction theory. They suggest that the head echo is due to diffraction from the discontinuity in the electron line density at the head of the train. They refer to bursts of ionisation associated with the visual flares observed along the trails of very bright meteors. This mechanism would be very sensitive to the off-specular angle.

Greenhow (1961) states that it is not necessary to postulate any mechanism for the production or dispersal of ionisation, other than normal processes of collision, diffusion and attachment. According to him, many of the "head echoes" can have reflecting regions as long as 100 km, with the ionisation persisting for many seconds after the passage of the meteor. These echoes are explained on the basis that the ionised columns behave as rough reflectors, losing completely the highly specular reflecting properties associated with faint meteors.

McIntosh (1963) makes a detailed analysis of 500 head echoes and discusses them in relation to various scattering mechanisms. He describes the meteor trail rather in terms of a blunt-nosed column than a narrow line. Since his radar is able to detect reflection from a sphere with a diameter of the order of 1 m, it is apparent that the end cap of an approaching meteor can produce a detectable head echo. By assuming a metallic cylinder with a hemispherical end cap and comparing radar cross sections for specular and end-on reflection, he obtains a target of 350 m radius – much larger than any theoretical predictions and estimated average trail radii. In addition, only approaching meteor could be observed.

During the following 25 years none of the models seem to have been able to explain all the observational features. Jones et al. (1988) introduced the water cluster ions and their fast dissociative recombination as a solution for the problem of removing the head echo ionisation. Jones and Webster (1991) reported observations of more than 700 head echoes. Their data was taken during 25 years from different meteor showers. They could state that the appearance of head echo could not be predicted in terms of meteor showers, brightness or elevation: it seemed to be stochastic. That stochastic source might be a composite meteoroid model with a loosely bound lower boiling point matrix ablating earlier in the entry process. Finally, they conclude that a prerequisite for a proper head echo scattering theory is a detailed knowledge of the ionised coma in the vicinity of a single meteoric grain.

A suggested solution for the head echo problem was presented by Jones et al. (1999). They describe a dilute plasma around the meteoroid, a plasma which is easily penetrated by radio waves until the electron density reaches a certain critical value determined by the radio wavelength. After that the plasma is no longer transparent to the radiation but reflects much like a good conductor. The idea is in principle the same as for the EISCAT model presented by Wannberg et al. (1996), and described in the next section.

3 EISCAT observations and the overdense model

The foundation for the overdense head echo scattering model for EISCAT was presented by Wannberg et al. (1996) based on EISCAT VHF/UHF dual frequency observations on head echo altitude distributions and estimated target sizes, and has been further reported by Westman et al. (1997, 2004). The reported high vector velocities from the tristatic EISCAT observations (Janches et al., 2002) also support the model requiring high-energy meteoroid-atmosphere interactions.

Head echo altitude distributions from simultaneous UHF and VHF observations in August 1993 show a clear difference in the altitudes (Westman et al., 2004). A parameter to compare the altitude distributions, a "cutoff height", was defined, (i.e. the altitude below which 90% of the head echoes are observed). The parameter is related to the upper edge of the distribution since it is there where the essential interaction for the ionising model occurs. At the lower edge other processes, such as ablation, might contribute. The cutoff height for the VHF is 109.8 ± 0.3 km and for the UHF it is 104.0 ± 0.2 km. A careful analysis is done to show that biases due to different UHF and VHF beam widths are 10% at most of the observed 5.8 km cutoff height differences. Thus, the differences in the altitude distributions are real. A recent theoretical work presenting a full-wave solution on radar wave scattering from meteor head echo plasma by Close et al. (2004) also confirms the existence of this feature.

Head echo targets seem to be larger for VHF than even for simultaneous UHF meteors, indicating that the shorter wavelength UHF penetrates deeper into the ionised target. The target sizes can be estimated by assuming that the signal temperature is proportional to the target size. The radar beam power density follows normal distribution. Even the scattered head echo strength follows the distribution as the meteor is passing the beam. With the present EISCAT one cannot say how far from the beam centre the meteor goes. Thus, all observed meteors are assumed to pass the middle

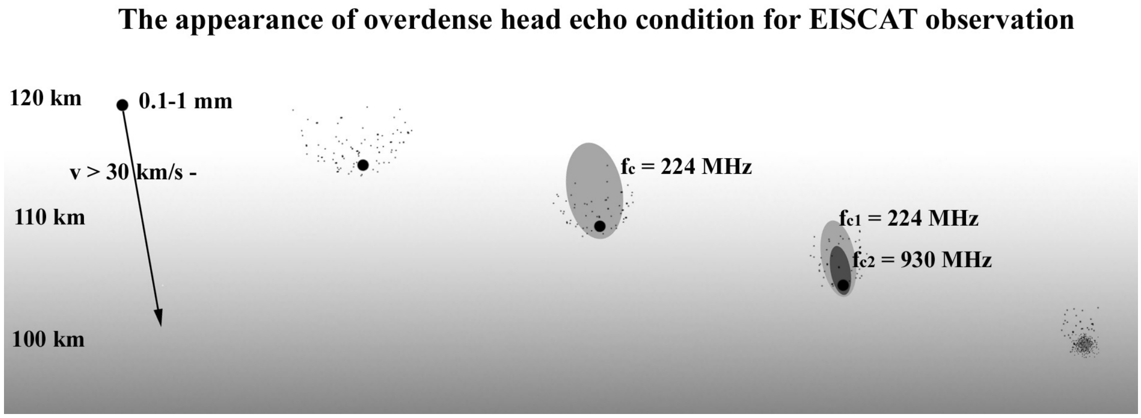

Fig. 1. The meteoroid-atmosphere interaction model based on EISCAT dual frequency observations. The ionized target becomes observable for the EISCAT 224 MHz VHF radar when it reaches the overdense condition at about 110 km. Some six kilometers further down, the effect of further ionization and increased atmospheric density compresses the target to reach the overdense condition, even for the EISCAT 930 MHz UHF radar waves. As the VHF waves do not reach as deep in the target as the UHF, the VHF target is slightly larger than the UHF one. If the geocentric velocity of the meteoroid is 50 km/s, every step in the process occurs with a 0.1-s interval. (Adapted from Pellinen-Wannberg, 2004.)

of the beam, which leads to an underestimation of the sizes of the particles which pass beside it. The signal temperature from the small meteor target is compared to the signal temperature of the whole observing volume, which is the 500-m radius cylinder of the EISCAT UHF radar beam and the 2 km$\times$3 km elliptic cylinder for the VHF beam at the 100-km range. The target sizes are obtained by assuming that the equivalent number of scattering electrons is compressed to a ball or coma of the size where they would reach the critical frequency corresponding to the monitoring frequency. The radii for UHF targets are 1–2 cm and for VHF 2.7–4.7 cm. (Wannberg et al., 1996; Westman et al., 2004), while the meteoroid sizes are 0.1–1 mm (Pellinen-Wannberg et al., 1998). The sizes of the scattering targets are of the same order of magnitude as predicted in the theoretical work by Close et al. (2004) in their Fig. 3.

The velocity is one of the basic parameters to estimate when observing meteors by any method. The tristatic EISCAT UHF can observe the true vector velocities for meteoroids that enter the common observing volume. The rates are low, but the results are very accurate. A set of tristatic meteors was analysed by Janches et al. (2002). In general, the observed vector velocities are high. The velocity values of the ten tristatic EISCAT meteors varied between 38.7 and 85.7 km/s, while the mean value was 64.7 km/s. Close et al. (2002a) report from the ALTAIR radar absolute velocities averaging 52 km/s at VHF and 65 km/s at UHF. Close et al. (2002b) report values down to 30 km/s, but notice an absence of 20 km/s sporadics apparently due to the limiting capability of the radar. Observing lower velocities is possible, but most likely a larger particle which is less probable is needed. The observed high velocities indicate that a high-energy interaction is required for the meteoroid to become observable through the head echo process.

The overdense model as presented here discusses the plasma interaction in the immediate vicinity of the meteoroid. The limit for the target is the limit of the overdense ionisation, which is a few centimetres in radius and depends on the observing frequency. Thus, there is also enhanced ionisation outside this limit. The ionisation is controlled by the ionising process of the atoms and molecules on the meteoroid surface, in the atmosphere and the compression of the ionised volume due to the penetration of the meteoroid into the deeper and denser atmosphere. The ionisation produced corresponds to the expanding line density that is left behind the meteoroid.

Figure 1 shows a schematic view on the meteoroid-atmosphere interaction process along the meteoroid path, when it is penetrating the increasing density in the atmosphere based on the observations reported above (Pellinen-Wannberg, 2004). The VHF echo appears when the plasma generated in the interaction process reaches the 224-MHz critical density of $6\times10^{14}\,\mathrm{m}^{-3}$. A few kilometres further down, the plasma density increases partly due to further ionisation and partly due to the compression of the interaction volume, so that even the critical frequency corresponding to EISCAT 931 MHz, $1\times10^{16}\,\mathrm{m}^{-3}$ is reached. At the same time the VHF echo is still observed. In dual frequency observations of a common volume by EISCAT, every UHF meteor is also seen in VHF.

4 Discussion

The overdense meteor head echo scattering model presented above and based initially on EISCAT observations corresponds well to other HPLA radar observations, such as those done with the multifrequency ALTAIR radars (Close et al., 2002a). The Arecibo radar is an order of magnitude larger in both aperture and sensitivity. The rates at Arecibo are also very high and observed velocities range to values below 10 km/s (Mathews et al., 1997; Janches et al., 2000). Probably Arecibo can observe much fainter echoes than the other facilities. It is suggested that the Arecibo meteor head echoes arise from underdense scattering (Mathews et al., 1997; Mathews, 2004). Even in this model the target sizes are small – about 17 cm (wavelength $\lambda/4$) for the 430 MHz – within the range of constructive interference.

The full-wave solutions developed by Close et al. (2004) for scattering from meteor head echo plasma show that both overdense and underdense scattering exist. The most sensitive radars probably observe both kinds of head echoes. This will be studied for EISCAT VHF in the near future.

The suggested head echo scattering process should be related to head echo observations on meteor radars. The problems in the early head echo models were the stochastic appearance of these echoes, the large target sizes ranging from 1 m to 100 km, depending on model, and the rapid disappearence of the head echo ionisation. The true scattering target sizes depend on the monitoring wavelength, but are in any case much smaller than one meter at V/UHF. As the targets are small, the total amount of electrons is still small. The amount of the electrons ahead of the meteoroid corresponds to the amount of the electrons in the line density in the trail left behind the meteor. This can explain the problem of the rapidly vanishing ionisation. Since the head echoes observed with meteor radars are in general much fainter than the trail echoes, small variations in their size, orientation and even composition, such as that discussed by Jones and Webster (1991), might explain their stochastic observability.

The location of EISCAT at high latitudes offers some exciting challenges. A project to study the off-ecliptic component of the interstellar and interplanetary dust distributions has recently been initiated. As the instrument is sensitive for fast meteors, the method may well be applied to interstellars. On the other hand, the dust distribution at high latitudes is not well known yet, but the long period comets are assumed to feed this population (Mann et al., 2000). Tristatic EISCAT observations are well suited as input values for simulations of the off-ecliptic component of the solar system dust cloud.

5 Conclusions

After 13 years of observations of meteor head echoes at EISCAT and other HPLA radar facilities around the world, one can conclude that using HPLA radars for meteor studies is a well established method, which is well-suited for studying in detail many aspects of the meteoroid impact process in the atmosphere. EISCAT has two radars located at the same site in Tromsø – the 930 MHz UHF and the 224 MHz VHF. These can observe the same meteors at different wavelengths and achieve deeper understanding of the true scattering process. It now appears that we have both sufficiently detailed multi-frequency observations and the theoretical basis necessary to solve the old problem concerning meteor head echoes.

Other topics that can be studied with this method, if a tristatic facility is available, are true vector velocities and retardations, angle dependence of the scattering process, as well as target sizes. The location of the EISCAT facility at high latitudes, together with the tristatic observing capabilities, gives EISCAT the potential to become one of the most powerful instruments for studying the off-ecliptic extra-terrestrial dust populations.

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References

Browne, I. C. and Kaiser, T. R.: The radio echo from the head of meteor trails, J. Atmos. Terr. Phys., 4, 1–4, 1953.

Close, S., Oppenheim, M., Hunt, S., and Duryd, L.: Scattering characteristics of high-resolution meteor head echoes detected at multiple frequencies, J. Geophys. Res., 107(A10), 1295, doi:10.1029/2002JA009253, 2002a.

Close, S., Hunt, S., Minardi, M., and McKeen, F.: Characterization of Leonid meteor head echo data collected using the VHF/UHF Advanced Research Projects Agency Long-Range and Tracking Radar, Radio Sci., 37(1), doi:10.1029/2000RS002602, 2002b.

Close, S., Oppenheim, M., Hunt, S., and Coster, A.: A technique for calculating meteor plasma density and meteoroid mass from radar head echo scattering, Icarus, 168, 43–52, 2004.

Evans, J. V.: Radio-echo studies of meteors at 68-centimeter wavelength, J. Geophys. Res., 70, 5395–5416, 1965.

Evans, J. V.: Radar observations of meteor deceleration, J. Geophys. Res., 71, 171–188, 1966.

German, M. J. and Mathews, J. D.: Interference detection and correction applied to incoherent scatter radar power profile measurements, Radio Sci., 21, 745–751, 1986.

Greenhow, J. S., Head echoes from meteor trails, J. Atmos. Terr. Phys., 22, 64–73, 1961.

Greenhow, J. S. and Watkins, C. D.: The characteristics of meteor trails observed at a frequency of 300 Mc/s, J. Atmos. Terr. Phys., 26, 539–558, 1964.

Hey, J. S., Parsons, S. J., and Stewart, G. S.: Radar Observations of the Giacobinid Meteor Shower, Mon. Not. R. Astron. Soc., 107, 176–183, 1947.

Janches, D., Mathews, J. D., Meisel, D. D., and Zhou, Q.: Micrometeor Observations using the Arecibo 430 MHz Radar: I. Determination of the Ballistic Parameters from Measured Doppler Velocity and Deceleration Results, Icarus, 145, 2, 2000.

Janches, D., Pellinen-Wannberg, A., Wannberg, G., Westman, A., Häggström, I., and Meisel, D. D.: Tristatic observations of meteors using the 930 MHz EISCAT radar system, J. Geophys. Res., 107(A11), 1389, doi:10.1029/2001JA009205, 2002.

Jones, J. J., Mitchell, B. A., and McIntosh, B. A.: Cluster ions and the meteor head echo, Mon. Not. R. Astr. Soc., 232, 771, 1988.

Jones, J. and Webster, A. R.: Visual and radar studies of meteor head echoes, Planet. Space Sci., 39, 873, 1991.

Jones, J., Jones, W., and Halliday, I.: The head echo problem – a solution at last?, Meteoroids 1998 proceedings, Astron. Inst., Slovak Acad. Sci., 29–36, 1999.

Mann, I., Krivov, A., and Kimura, H.: Dust cloud near the sun, Icarus, 146, 568–582, 2000.

Mathews, J. D., Hunter, K. P., Meisel, D. D., Getman, V. S., and Zhou, Q.: Very High Resolution Studies of Micrometeors Using the Arecibo 430 MHz Radar, Icarus, 126, 157, 1997.

Mathews, J. D.: Radio science issues surrounding HF/VHF/UHF radar meteor studies, J. Atmos. Solar-Terr. Phys., 66, 3, 285–299, 2004.

McIntosh, B. A.: Experimental study of the amplitude of radar meteor-head echoes, Can J. Phys., 41, 355–371, 1963.

McKinley, D. W. R. and Millman, P. M.: A phenomenological theory of radar echoes from meteors, Proc. I.R.E., 37, 364–375, 1949.

Millman, P. M. and McKinley, D. W. R.: A note on four complex meteor radar echoes, J. Royal Astron. Soc. Canada, 42, 121–130, 1949.

Pellinen-Wannberg, A. and Wannberg, G.: Meteor observations with the EISCAT UHF incoherent scatter radar, J. Geophys. Res., 99, 11 379–11 390, 1994.

Pellinen-Wannberg, A., Westman, A., Wannberg, G., and Kaila, K.: Meteor fluxes and visual magnitudes from EISCAT radar event rates: a comparison with cross section based magnitude estimates and optical data, Ann. Geophys., 16, 1475–1485, 1998, **SRef-ID: 1432-0576/ag/1998-16-1475**.

Pellinen-Wannberg, A.: The EISCAT meteor-head method – a review and recent observations, Atmos. Chem. Phys., 4, 649–655, 2004,
SRef-ID: 1680-7324/acp/2004-4-649.

Steel, D. I. and Elford, W. G.: The height distribution of radio meteors: comparison of observations at different frequencies on the basis of standard echo theory, J. Atmos. Terr. Phys., 53, 5, 409–417, 1991.

Wannberg, G., Pellinen-Wannberg, A., and Westman, A.: An ambiguity-function-based method for analysis of Doppler decompressed radar signals applied to EISCAT measurements of oblique UHF-VHF meteor echoes, Radio Sci., 31, 497–518, 1996.

Westman, A., Wannberg, G., and Pellinen-Wannberg, A.: Meteor head echo height effect observed by the European Incoherent Scatter UHF and VHF radars, in: Assar Westman's Ph.D. thesis, IRF Scientific Report, 246, 1997.

Westman, A., Wannberg, G., and Pellinen-Wannberg, A.: Meteor head echo height distributions and the meteor impact mechanism observed with the EISCAT HPLA UHF and VHF radars, Ann. Geophys., 22, 1575–1584, 2004,
SRef-ID: 1432-0576/ag/2004-22-1575.

Zhou, Q. and Mathews, J. D.: A spectral technique for the detection and correction of coherent interference effects on incoherent scatter radar power profiles, Radio Sci., 29, 1173–1177, 1994.